

# INDEX

Page numbers followed by f and t indicate figures and tables, respectively.

- A**
- Acceleration
    - block, 534
    - defined, 534
    - head, 171–172
    - typical, 534
  - Accumulator, flow transients of, 344–346, 345f
  - Acidity/alkalinity (pH)
    - pump selection and, 23
  - Acoustic boundary conditions
    - and resonance, 488–490, 488f–490f
    - acoustic resonance condition of piping network, 488–490, 488f–490f
  - Acoustic transfer matrix
    - for centrifugal compressor, 479–480, 479f
    - for pipe element, 464–471, 466f, 471f
    - damping (attenuation) on, 468–471, 471f
    - mean flow on acoustic TM for pipe element, 467–468
    - for throttle element, 472–478, 473f, 474t, 475f, 476f, 477f
    - ball valve, 476, 476f, 477f, 478f
    - globe valve, 476–478
    - orifice plate, 475, 475f
    - for a volume element, 478–479, 478f
  - Active bearings, 560–561
  - Adaptive control algorithms, 223
  - Additives, operational hazards of, 9
  - Adiabatic compression, 243, 255
  - Adjustments, compressor performance, 272–274
  - Aeroderivative gas turbines, 280, 281–282, 291–292
  - Affinity laws, 148, 149f
  - Aftercooler, defined, 198
  - Air compressor surge, 286–287
  - Air cooled heat exchanges, 70
  - Air coolers, 70
  - Air intake system, gas turbines, 286
  - Alkalinity
    - pump selection and, 23
  - American Gear Manufacturers Association (AGMA), 329–330
  - American Petroleum Institute (API), 97
    - API 541, 310
    - API 546, 310
    - API 614, 194, 203, 233, 291
    - API 616, 305
    - API 617, 209, 228, 233, 261
    - API 618, 201, 203, 254
    - API 671, 329
  - American Petroleum Institute (API) gravity, SG and, 133–136
  - American petroleum Institute (API 520) standards, 526–527
  - American Society of Mechanical Engineers (ASME), 97
  - Ampliflow™, 218
  - Analytical pipe model, 449–450
  - Anchor bolts, 183, 184
  - Anechoic (non-reflective), acoustic boundary conditions, 489
  - ANSI/HI 9.6.8, 516–517
  - ANSI pressure limitations, pipeline design and, 21, 34
  - Anti-icing systems, 288–289
  - AP-42 emission factors, 613
  - API, *see* American Petroleum Institute (API)
  - API 610, 516–517, 517f
  - API 688 document, 516
  - API 618 reciprocating compressors, 516
  - API 674/675 reciprocating pumps, 516
  - API 619 rotary (screw) compressors, 516
  - API 676 rotary (progressive cavity) pumps, 516
  - API RP 14E recommendations (pipe sizing), 39
  - API 618 Standard, 502–510, 503f
    - acoustic shaking forces, 504
    - compressor mechanical model analysis, 504
    - Design Approach 2, 503, 503f
    - Design Approach 3, 503–504
    - Design Approach (DA) 1, 503, 503f
    - Design Approach 1 pulsation limits, 507–509
    - earlier version (4th edition), 502
    - general criteria, 505–507
    - maximum allowable non-resonant shaking forces, 509–510
    - mechanical analysis, 502–503
    - piping system analysis, 504–505
    - pulsation analysis, 502–503
    - pulsation guidelines, 505
    - purpose of, 502
    - separation margin, 504
    - for slow and medium-speed machines, 502
  - API 674 Standard, 510–512
  - Application torque, calculation, 324
  - ASME, *see* American Society of Mechanical Engineers (ASME)

- ASME Power Test Code PTC 10, 228, 261
- Aspects, compressor performance, 237–247
- behavior, 243–244
  - efficiency, 244–245
  - flow, 245
  - gas properties, 237, 238–243
    - compressibility and molecular weight, 238–240
    - EOS, 241–243
    - ideal gas laws, 237, 238
    - ratio of specific heats, 240–241
  - general, 237
  - head, 244
  - nomenclature, 237, 238t
  - power, 245–247
- Asymmetric series compressors with spare unit, 79–80, 81f
- Attenuation
- acoustic transfer matrix for pipe element and, 468–471
- Aude equation, 24
- Automated surge relief installation, 60–61
- Auxiliary system level control, 92
- Axial diffusion coefficient, 46
- Axial-flow compressor, 285
- Axial-flow pumps, 106
- Axial split (casing), 206
- Axial thrust, calculation of, 208, 209
- B**
- Balanced Noise Criterion (NCB) curves, 598
- Balance drum
- defined, 208
  - forces, 208, 209f
- Balance piston
- defined, 208
  - forces, 208, 209f
- Balancing, rotordynamics and, 561–563, 562f–563f
- Ball valves, 44
- acoustic transfer matrix for throttle element, 476, 476f, 477f, 478f
- Barrel-type centrifugal compressors, 203, 204f
- Batch contamination
- in liquid pipelines, 45
- Beam-type compressors, wet seals for, 214
- Bearings
- active, 560–561
  - centrifugal compressors, 209–211
  - externally pressurized, 560
  - gas turbines, 289–291
  - IGCC, 233–234
  - magnetic, 560–561
  - pressurized oil, 560–561
  - reciprocating compressors, 193, 194–196
  - regular internally-pressurized fluid film, 560
  - rotordynamics and, 560–561
- Bed section, of compressor frame, 182–183
- Behavior, compressor, 243–244
- Benedict-Webb-Rubin equations, 228
- Benedict-Webb-Rubin-Starling (BWRS) equation, 242
- Bently Pressurized (orifice) Bearing Company, 211
- Bingham fluids, 21, 22f
- Block acceleration, 534
- Blockage, degradation mechanism, 265
- Blowdown
- noise suppression during, 496–499, 497f–499f
- Blowdown, station and gas pipeline, 444–457, 445f
- comparison between models, 450–453
  - non-isothermal blowdown, 453–457
  - pipe model, 449–450
  - volume model, 446–449
- Booster compression, 6
- Booster pumps, 54
- Boundary conditions, 342–346
- flow transients
    - across other elements, 343–344, 343f–344f
    - of an accumulator, 344–346, 345f
- Bowtie diagrams, 8
- Boyle's law, 238, 243
- Brake horsepower, compressor, 250
- Brayton cycle, 302, 303f
- Broadband shock-associated noise, 603
- Buildings, compressor station, 95
- Bureau of Land Management, 97
- Bypass check valve, 36, 43
- C**
- Canadian Energy Pipeline Association (CEPA), 7
- CAN/CSA Z662 (safety standards), 7
- CAN/CSA Z767-17 (safety standards), 7
- Capacity
- compressors, 245
  - control, reciprocating compressors, 187, 188f, 189f
  - reciprocating compressors, 247–249
- Carbon monoxide (CO), formation, 295
- Cascading effect, 70
- Case studies and examples
- ethylene pump, 365, 367–369, 367f–368f
  - pulsation and vibration analysis
    - multiple source pulsation, 521–523, 522f
    - pulsation generated by a reciprocating compressor, 523–525, 523f–525f
    - single-source pulsation, 520–521, 520f–521f
  - styrene transfer system, 361–365, 361f–362f, 363f, 364f–365f, 366f
- Case study pulsation examples, 518–525
- multiple source pulsation, 521–523, 522f
  - high-flow case, 523
  - intermediate-flow case, 523
  - low-flow case, 523
  - pulsation generated by a reciprocating compressor, 523–525, 523f–525f
  - single-source pulsation, 520–521, 520f–521f
- Casing (axial split), 206

- Causes (bowtie diagram), 8
- Cavitation, 499, 500f
- Cavitation and column separation, 358–361
  - overview, 358–359
  - steam condensation-induced water hammer, 359–361, 360f
- Cavitation in centrifugal pumps, 154–160
  - damage due, 154–155
  - effects of, 155
  - formation, 155, 157f
  - NPSH, 157–158
  - NPSHA, 158, 159f
  - NPSHR, 158–159, 160f
  - phenomenon, 154–155
  - reducing, 155
- CEM measurements, 613–615, 614f, 615f
- Centaur, 281
- Centrifugal booster pumps, 105f
- Centrifugal compression systems
  - blowdown, *see* Blowdown, station and gas pipeline
  - check valve, *see* Check valve
  - dynamics
  - dynamic instabilities, fundamentals of, 372–386
    - complex compression systems, 375–379, 378f, 379f
    - control dynamics, 379–381, 381f
    - simple compression systems, 372–374, 372f–373f, 374f
    - solution techniques, 382–386, 382f–383f, 384f, 385f, 386f
  - ESD, *see* Emergency shutdown (ESD)
  - overview, 371–372
  - relief valve, *see* Relief valve
  - dynamics
- Centrifugal compressors, 203–229
  - acoustic transfer matrix for, 479–480, 479f
  - advantages and disadvantages of, 334
  - bearings, 209–211
  - controls and monitoring, 220–223
  - design(s)
    - general, 203–205, 206f
    - standards, 228–229
  - flow (capacity), 245
  - forced vibration in, 551
  - internals and sealing, 205–209
  - lubrication system, 211, 213
  - mechanical analysis of piping systems, 584–588, 586f, 587f
  - multi-stage, 551
  - performance, 254–267
    - degradation monitoring, 264–266, 267f
    - dynamic performance characteristics, 254–260
    - general, 254
    - mixture composition on, 262–264
    - selection and sizing, 260–261
    - testing, 261–262
  - physical operation, 223–228
    - diffuser, 228
    - fluid properties, effect of, 228
    - impellers, 224–227
    - performance characteristics, 223–224
  - pressure–volume characteristic, 270, 271f
  - rotordynamics and, 551–552
  - sealing system, 213–220
    - dry gas seals, 216–219
    - emerging gas seal technology, 220
    - general, 213–214
    - wet oil seals, 214–215
  - self-excited vibration in, 551
  - subsynchronous vibration in, 551
- Centrifugal impeller design theory, 141–143
- Centrifugal pumps, 104–118; *see also* Pump(s)
  - advantages, 100
  - axial-flow pump, 106
  - centrifugal action, 108
  - components, 108
  - configuration, 107
  - design, 106–109, 110f, 111f
  - impeller, 107–109
  - functioning of, 106–107
  - limits, 163–166
    - minimum flow, 163
    - re-circulation, 164–166
    - temperature rise, 163–164
  - mechanical seals, 109–114, 115f
  - mixed-flow pumps, 106
  - modifications, 150, 151f–153f
  - nozzle loading, 114–118
  - operational hazards of, 9
  - performance of
    - affinity laws, 148, 149f
    - cavitation in, 154–160
    - centrifugal impeller design theory, 141–143
    - coverage chart, 138
    - impeller curve characteristics, 145–147
    - impeller selection, 138–140
  - pipeline-pump operational control, 148–150
  - pump performance curves, 137–138, 139f
  - pump power and, 150
  - radial flow pumps, 105, 106f
  - rotordynamics and, 553–554
  - specific speed, 143–145, 146f
  - system curve, 140, 141f
  - types, 104–106
    - viscous liquids and, 160–163
- Centrifugal pumps, dynamic behavior, 346–353
- dynamic equation, 348, 351–352
- full pump characteristics, 347–348, 349f, 350t–351t
- homologous relations, 347
- pump and motor inertias, 352–353, 352f, 353f
- CEPA, *see* Canadian Energy Pipeline Association (CEPA)
- Characteristic curves, pump, 145–147
- Characteristics
  - centrifugal compressors, dynamic performance, 254–260
  - basic performance curves, 254–257
  - fan laws, 257–258
  - limits, 258–260
  - gas turbine performance, 299, 300, 301, 302f, 303f
  - system, 267–276
    - adjustments, 272–274
    - comparison, 270, 271f
    - curves, 267–270
    - general, 267

- operating considerations, 274–276
- operating limitations, 271–272
- Charles' law, 238
- Chattering, pressure relief valves (PRV), 526
- Check valve dynamics, 411–427
  - compression recycle system and, 425–427, 426f, 428f
  - counterbalance on maximum reverse velocity, 421–422, 422f
  - overview, 411–413
  - piston type check valves, 422–424, 422f
  - swing type check valves
    - description, 411–412, 412f
    - dynamic behavior of, 413–417, 414f, 416f–417f
    - slamming characteristics, 417–421
  - wafer type check valves, 424–425, 424f
- Chip detectors, 292
- Choke, 259, 260, 272
- Circular casing pump, 106
- CleanPac™, 218
- Clearance volume control, 187
- Closed, acoustic boundary conditions, 482–485
- Codes and standards, compressor, 96–97
- Combustion air/lube oil-water cooling, 70
- Combustion engines, internal, 320–323
  - advantages and disadvantages of, 333–334
  - design, 320–322
  - general, 320
  - integral engine/compressors, 322–323
- Compatibility
  - between driver and driven equipment, 331, 332, 333, 334
  - with existing equipment, 331, 332, 334
- Complex compression systems, 375–379, 378f, 379f
- Component matching, defined, 302
- Compressibility
  - correction, 250
  - gases, 238–240
- Compression
  - booster, 6
  - dependability for, 14–15
  - equipment, types, 75–76
  - field, 6
  - gas pipeline and, 5–6, 65
  - gas recovery, 5
  - gas storage, 6
  - ignition engines, 320
  - interchange, 6
  - lateral, 6
  - versus* looping, gas pipelines, 66f, 69–70
  - performance curve, 72f
  - recycle system, check valves
    - effect on, 425–427, 426f, 428f
  - requirements, 85–86
- Compressor Equipment Health Monitoring (CEHM) system, 620
- Compressors
  - centrifugal, *see* Centrifugal compressors
  - classification, 179, 180f
  - cost of operation, 73–74
  - design and operation, *see* Design and operation
  - drivers, *see* Drivers
  - hermetic, 315–317
  - IGCC, 231–234
  - mechanical model analysis, 504, 515f
  - performance, *see* Performance pipeline, overview, 179
  - reciprocating, *see* Reciprocating compressors
  - screw, 229–231
- Compressors arranged in series, recycle system around, 409–410, 409f, 410f–411f
- Compressor stations
  - buildings and weather protection, 95
  - codes and standards, 96–97
  - compression equipment, types, 75–76
  - compressor requirements, 85–86
  - cost of ownership, 74
  - driver requirements, 86–87
  - environmental considerations, 80
  - fire, 9–10
  - layout, 87, 88f
  - NPV analysis (case study), 77–78
  - number of units, 76–77
  - operating considerations, 74–75
  - parallel arrangement, 76
  - piping layout, 87, 89–90
  - “power” backup, 79
  - predictions of noise levels from, 601–607
  - scrubbers and filters, 90–91
  - series arrangement, 76
  - series-parallel arrangement, 76
  - spacing, 69
  - standby units, 78–80, 81f
  - unit auxiliary systems and, 92
  - unit control systems and, 92–95
  - usage scenario for pipeline stations (case study), 81–85
- Computational Fluid Dynamics (CFD) analysis, 626
- Configuration, pump, *see* Pump configurations
- Consequences (bowtie diagram), 8f, 9
- Constant area pipes, governing equation for, 339–341, 340t–341t
  - assumptions, 339
- Contaminants, in liquid fuels, 293
- Contamination in liquid pipelines, 44–52
  - DNV erosion model, 48, 49f, 49t
  - Zhang et al. erosion model, 48–50
- Control dynamics, 379–381, 381f
- Controlled engines, 613
- Control system
  - centrifugal compressors, 220–223
  - reciprocating compressors, 196
- Conversion factors, for pumps, 175–177
- Coolbrook–White equation, 24
- Cooling requirements, gas pipelines, 70
- Cooper Bessemer GMW family of engines, 322
- Cost
  - of compressor operation, 73–74
  - J-curves graph and, 68

- of ownership, compressor station, 74
- pipeline design and, 21–22
- Counter-swirl position, guide vanes, 273
- Coupling(s), 323–330, 558–560, 559f, 560f
  - connection, 324
  - diaphragm, 325, 326f
  - disc, 325, 326f
  - flexible, 325, 326f
  - fluid, 314, 315f
  - functions, 323
  - gear, 325, 558
  - general purpose, 323
  - lubricated gear, 325
  - much reduced deflection for torsionally soft, 560f
  - selection, 323, 324–325
  - soft
    - elastomeric, 327
    - steel-spring, 327
  - special purpose, 324
  - standards, 329–330
  - too stiff for motor/compressor set, 558
  - torsional analysis, 558
  - torsional vibration problem in reciprocating compressor installation, case study, 327, 328, 329f
- Coverage chart, centrifugal, 138
- Crank end (CE) cycle, 198
- Critical speeds, 272
- Cross-hole seismic testing, 514
- Crude oil, operational hazards of, 9
- Curves
  - performance, centrifugal compressors, 254–257
  - system characteristic, 267–270
- Cycling, pressure relief valves (PRV), 525
- Cyclone scrubber, 91f
- Cylinders, compressor, 183, 185–187
- D**
- Damage risk criteria (DRC), 592, 595
- Dampeners, 413
  - in liquid systems, 500
- Damping
  - acoustic transfer matrix for pipe element and, 468–471, 471f
- Darcy equation, 24–25
- Day–night equivalent level (DNL), 599
- DBB, *see* Double block and bleed capacity (DBB)
- Degradation monitoring, centrifugal compressor performance, 264–266, 267f
- Density, pipeline design and, 21, 22
- Dependability, pipeline system
  - characteristics, interrelationship between, 12
  - concept of, 11–12
  - framework over the life cycle for pipelines, 14f
  - functional and non-functional requirements, 12, 13f
  - for pumping and compression, 14–15
  - RAM models, 15–16, 16f, 17f
  - value of, 12–14
- Design and operation, 179–234
  - centrifugal compressors, 203–229
    - bearings, 209–211
    - controls and monitoring, 220–223
    - diffuser, 228
    - fluid properties, effect of, 228
    - general design, 203–205, 206f
    - impellers, 224–227
    - internals and sealing, 205–209
    - lubrication system, 211, 213
    - performance characteristics, 223–224
    - physical operation, 223–228
    - sealing system, 213–220
    - standards, 228–229
  - IGCC, 231–234
    - bearings, seals and gears, 233–234
    - design, 231–233
    - overview, 179, 180f
  - reciprocating compressors, 179–203
    - bearings and lubrication systems, 193, 194–196
    - capacity (flow) control, 187, 188f, 189f
    - considerations, 203
    - control system, 196
    - frame and cylinders, 183–187
    - gas cooling, 198
    - general design, 179–181
    - monitoring system, 197
    - optimization, 200–201
    - packings, 193, 194f
    - physical operation, 198–200
    - rod loading, 201–202
    - running gear, 181, 182–183
    - start-up and shutdown, 197
    - valves, 187, 189–192, 193f
  - screw compressors, 229–231
    - design, 229, 230f
    - operation, 230–231
- Design(s)
  - centrifugal pump, 106–109, 110f, 111f
  - considerations, electric motors, 310, 311f
  - gas turbines, 283–286
  - internal combustion engines, 320–322
  - liquid pipeline systems, 19–28
- Design standards
  - centrifugal compressors, 228–229
  - gas turbines, 305
  - reciprocating compressors, 203
- Diameter, cost of a pipeline and, 1
- Diaphragm coupling, 325, 326f
- Diesel engines, 320
- Differential pressure control, dry gas seals, 217
- Diffuser, centrifugal compressors, 228
- Diffuser pump, 106
- Digital no-flow timer (DNFT) switch, 196
- Dilatant fluids, 21, 22f
- Dilution, 135
- Dimensional analysis, performance of centrifugal compressors, 260
- Dimensionless variables, centrifugal pump, 347
- Direct-acting (steam) pump type, 99
- Disc couplings, 325, 326f



- Discharge piping for reciprocating pumps, 129
  - Discharge temperature
    - centrifugal compressors, 256
    - compressors, 271
    - reciprocating compressors, 251
  - Discharge valve, 187, 189f, 190, 191, 192f
  - DNV erosion model, 48, 49f, 49t
  - DNV Recommended Practice
    - RP-O501, erosion rate and, 50–52
  - Double block and bleed capacity (DBB), 44
  - Double-suction pump, 106
  - Dresser-Rand Datum C hermetic “compact” compressor, 316–317
  - Drip proof, 310
  - Driver and driven equipment unit control, 92
  - Driver operating characteristics, 86–87
  - Drivers, compressor, 279–335
    - couplings, 323–330
      - elastomeric soft, 327
      - flexible, 325, 326f
      - functions, 323
      - gear, 325
      - selection, 323, 324–325
      - standards, 329–330
      - steel-spring soft, 327
      - torsional vibration problem in reciprocating compressor installation, case study, 327, 328, 329f
    - drivers and driven equipment, comparison, 330–335
      - centrifugal compressors, advantages and disadvantages of, 334
      - electric motors, advantages and disadvantages of, 332–333
      - gas turbines, advantages and disadvantages of, 330–332
      - general factors, 330
      - internal combustion engines, advantages and disadvantages of, 333–334
      - reciprocating compressors, advantages and disadvantages of, 335
    - electric motors, 307–319
      - design considerations, 310, 311f
      - economics, 317–319
      - general, 307
      - hermetic compressors, 315–317
      - types, 307–310
      - variable speed drives, 310, 311–315
    - gas turbines, 280–307
      - advantages, 284
      - aeroderivative gas turbine lube oil system, 291–292
      - air compressor surge, 286–287
      - air intake system, 286
      - anti-icing systems, 288–289
      - bearings, 289–291
      - design, 283–286
      - design standard, 305
      - exhaust system, 289
      - fuel system, 292, 293–299
      - industrial gas turbine lube oil system, 292, 293f
      - performance, 299, 300–305
      - types, 280–283
      - variable compressor geometry, 287–288
      - waste heat recovery, 306–307
    - internal combustion engines, 320–323
      - design, 320–322
      - general, 320
      - integral engine/compressors, 322–323
      - overview, 279–280
  - Drivers and driven equipment, comparison, 330–335
    - centrifugal compressors, advantages and disadvantages of, 334
    - electric motors, advantages and disadvantages of, 332–333
    - gas turbines, advantages and disadvantages of, 330–332
    - general factors, 330
    - internal combustion engines, advantages and disadvantages of, 333–334
  - reciprocating compressors, advantages and disadvantages of, 335
  - reciprocating compressors, advantages and disadvantages of, 335
  - Drooping characteristic curve, 146, 147f
  - Dry-gas seals, 216–219
    - leakage rates, 625
    - recovering vent gas loss from, 624–634
  - Dry low emissions (DLE), 296
  - Dry low NO<sub>x</sub> (DLN), 296–297
  - Dual fuel system, 299, 301f
  - Duplex reciprocating pumps, 122f
  - Dynamic actuator/positioner, 380
  - Dynamic behavior, pumping systems, 339–369
    - boundary conditions, 342–346
    - cavitation and column separation, 358–361
    - centrifugal pumps, *see* Centrifugal pumps
    - examples and case studies, 361–369
    - four quadrant charts, 354–357, 355f, 357f
    - governing equation for constant area pipes, 339–341, 340t–341t
    - overview, 339
    - solution techniques, 341–342, 342f
    - water hammer, 357–358
  - Dynamic Characteristic Curve (DCC), 414
  - Dynamic equation, centrifugal pumps, 348, 351–352
  - Dynamic forces, by reciprocating compressor, 183–184
  - Dynamic performance characteristics, centrifugal compressors, 254–260
    - basic performance curves, 254–257
    - fan laws, 257–258
    - limits, 258–260
  - Dynamic pulsation dampener, 125
- E**
- Economics, driver, 317–319
  - Effects (bowtie diagram), 8f, 9
  - Efficiencies

- compressor performance, 244–245, 250, 256
  - thermal, 331, 332, 334
  - VFD, 314
  - Elastomeric soft couplings, 327
  - Elbow
    - DNV RP O501 erosion model for, 50–52
    - flow distortion and, 41f
  - Electric compressor drivers *versus* gas, 69–70
  - Electric motors, 307–319
    - advantages and disadvantages of, 332–333
    - design considerations, 310, 311f
    - economics, 317–319
    - general, 307
    - hermetic compressors, 315–317
    - types, 307–310
    - variable speed drives, 310, 311–315
      - fluid coupling, 314, 315f
      - VFD, 310, 311–314
  - Elevation profiles, gas pipeline, 72f
  - EMD station, 75
  - Emergency shutdown (ESD), 94, 95f, 386–410
    - effects of compressor performance characteristics, 389–393, 389f, 390f, 392f–393f
    - inertia number, 405–408, 407f–408f, 407t
    - integrally-gearred compression systems, 402–405, 403f, 403t, 404f–405f
    - recycle system around compressors arranged in series, 409–410, 409f, 410f–411f
    - rotor inertia on, 393, 394f, 395f
  - Emerging gas seal technology, 220
  - Emission calculations (case study), 84–85
  - Emissions
    - exhaust, 331, 332, 334
    - fuel system, 294–297
    - noise, 331, 332, 334
  - Enclosures, characteristics, 310
  - End cover (radial split), 206
  - Energy Institute, 571
  - Engine-driven screw compressor, 229, 230f
  - Engines
    - capacity curve, 252
    - controlled, 613
    - jacket water cooling, 70
    - uncontrolled, 613
  - Engines, internal combustion, 320–323
    - advantages and disadvantages of, 333–334
    - design, 320–322
    - general, 320
    - integral engine/compressors, 322–323
  - Enthalpy diagram, for Brayton cycle, 302, 303f
  - Entropy diagram, for Brayton cycle, 302, 303f
  - “Entropy spots,” 607
  - Environmental considerations, compressor station, 80
  - Environmental issues, 591–593
    - designing for environmental requirements, 593
  - Environmental issues, compressor and pump stations
    - capturing vent gas from dry gas seals, innovations in, 624–634; *see also* Supersonic ejectors
    - noise measurement, 594–607; *see also* Noise, compressor and pump stations
    - noise criteria limits, 595–600, 597t, 598f, 599f, 600t
    - noise level parameters, 594–595
    - predictions of noise levels from compressor stations, 601–607
    - NOx emissions from gas turbines, 612–623
    - overview, 591–593
  - Environmental Protection Agency, 97
  - Equations of state (EOS), gas properties, 241–243
  - Erosion, impeller, 261
  - Erosion model
    - DNV model, 48, 49f, 49t
    - DNV Recommended Practice RP-O501, 50–52
    - Zhang et al., 48–50
  - ESD, *see* Emergency shutdown (ESD)
  - Ethylene pump, 365, 367–369, 367f–368f
  - Euler’s theory, 142
  - Excitation mechanisms
    - mechanical analysis of piping systems, 563–564, 564f
  - Exhaust emissions, 331, 332, 334
  - Exhaust system, gas turbines, 289
  - Expansion chambers, 490–492, 491f, 492f, 524f, 525
  - Expenditures, operating, 1
  - Explosion proof, 310
  - Externally pressurized bearings, 560
  - Externally Pressurized Porous (EPP) Gas Bearing Technology, 220
- F**
- Facility Integrity Management Program (FIMP), 7
  - Failure modes and effects analysis, 8
  - Fan laws, centrifugal compressors, 257–258
  - Fast start-up valve positions, 37–38
  - Fault tree analysis, 8
  - Field compression, 6
  - Field tests/testing
    - gas turbine performance, 305
    - relief valve dynamics, 441–444, 442f, 443f–444f
  - Filters, compressor station, 90–91
  - FIMP, *see* Facility Integrity Management Program (FIMP)
  - “Fin-fan” coolers, 70
  - 1st stage supersonic ejector, 625–632, 625f, 626f, 627f, 630f, 631f, 632
  - Fitting limitations, 34
  - Flange–flange coupling connection, 324
  - Flange–hub coupling connection, 324
  - Flashing, 499

- Flat characteristic curve, 146, 147f
  - Flexible couplings, 325, 326f
  - Floating ring oil seals, 214
  - Flow
    - for compressors, 245
    - reciprocating compressors, 247–249
  - Flow control
    - dry gas seals, 217
    - reciprocating compressors, 187, 188f, 189f
  - Flow distortion, double-suction pump, 41f
  - Flow-generated pulsation from throttling elements, 480–482, 481f–482f
  - Flow-generated single-tone pulsation from closed end side branch, 482–485, 483f–484f
  - Flow transients
    - across other elements, 343–344, 343f–344f
    - of an accumulator, 344–346, 345f
  - Fluid coupling, 314, 315f
  - Fluid hammer, 357–358; *see also* Water hammer
  - Fluid properties, effect of, 228
  - Fluttering, pressure relief valves (PRV), 525–526
  - Forced response analysis, 572–576
  - Forced vibration, 551
  - Force-feed lubrication system, 196
  - Fouling, 261, 265
  - Foundations, compressor, 183–184
  - Four quadrant charts, pump, 354–357, 355f, 357f
  - Frame, reciprocating compressors, 183–187
    - integral compressor, 185
    - separable compressor, 184–185
  - Free turbine, defined, 283
  - Frequency drive, VFD, 310, 311–314
  - Friction head
    - liquid pipeline systems, 24
  - Fuel system, 292, 293–299
    - dual, 299, 301f
    - emissions, 294–297
    - liquid, 299, 300f
    - LNG, 297
    - natural gas, 297–299
    - types, 292, 293–294
  - Fuel usage (case study), 81–84
  - Full-scale factory testing, centrifugal compressors, 261–262
  - Functional requirements, dependability, 12, 13f
  - Functions, coupling, 323
  - G**
  - Gas coolers, 91, 92f
  - Gas cooling, reciprocating compressors, 198
  - Gas Machinery Research Council, 571
  - Gas pipeline systems, 4–6
    - booster compression, 6
    - buildings and weather protection, 95
    - codes and standards, 96–97
    - components of, 5
    - compression facilities and, 5–6
    - compressor station configuration
      - compression equipment, types, 75–76
      - compressor requirements, 85–86
      - driver requirements, 86–87
      - environmental considerations, 80
    - NPV analysis (case study), 77–78
    - number of units, 76–77
    - operating considerations, 74–75
    - parallel arrangement, 76
    - series arrangement, 76
    - series-parallel arrangement, 76
    - standby units, 78–80, 81f
    - usage scenario for pipeline stations (case study), 81–85
  - compressor station spacing, 69
  - cooling requirements, 70
  - cost of compressor operation, 73–74
  - field compression, 6
  - gas coolers, 91, 92f
  - gas recovery compression, 5
  - gas storage compression, 6
  - gas *versus* electric compressor drivers, 69–70
  - hydraulics, 65, 66f
  - hydraulic simulation, 70–73
  - hydraulics profile, 71f
  - interchange compression, 6
  - lateral compression, 6
  - looping *versus* compression, 66f, 69–70
  - network, 70, 71f
  - optimization process, 65–69
    - alternatives, 68–69
    - considerations, 65–66, 69
  - pressure regulation methods, 65
  - safety systems and environmental controls, 96
  - scrubbers and filters, 90–91
  - station and unit auxiliary systems, 92
  - station and unit control systems, 92–95
  - station layout, 87, 88f
  - station piping layout, 87, 89–90
  - transmission, 6
- Gas properties, for compression performance, 237, 238–243
- compressibility and molecular weight, 238–240
- EOS, 241–243
- ideal gas laws, 237, 238
- ratio of specific heats, 240–241
- Gas recovery compression, 5
- Gas storage compression, 6
- Gas turbines, 280–307, 554
  - advantages and disadvantages of, 284, 330–332
  - aeroderivative, 280, 281–282, 291–292
  - air compressor surge, 286–287
  - air intake system, 286
  - anti-icing systems, 288–289
  - basic design, 283–286
  - bearings, 289–291
  - design standard, 305
  - exhaust system, 289
  - fuel system, 292, 293–299
    - dual, 299, 301f
    - emissions, 294–297
    - liquid, 299, 300f
    - LNG, 297
    - natural gas, 297–299
    - types, 292, 293–294



- industrial gas turbine lube oil system, 292, 293f  
 NOx emissions from, 612–623  
 performance, 299, 300–305  
   calculations, 302, 303f, 304–305  
   characteristics, 299, 300, 301, 302f, 303f  
   field testing, 305  
   rotordynamics and, 554  
   types, 280–283  
   variable compressor geometry, 287–288  
   waste heat recovery, 306–307  
 GasTurb™, 302  
 Gearboxes, 558–560, 559f, 560f  
 Gear(s)  
   couplings, 325, 558  
   IGCC, 233–234  
 General criteria, API 618 Standard, 505–507  
 General Electric, 280, 281, 282f  
 Geometry, variable compressor, 287–288  
 Globe valve  
   acoustic transfer matrix for throttle element, 476–478  
 GMRC design guidelines  
   for high-speed reciprocating compressor packages for natural gas transmission & storage applications, 513–516  
 Governing equation for  
   constant area pipes, 339–341, 340t–341t  
 Groupe Européen de Recherches Gazières (GERG) EOS, 242–243  
 Guide vanes  
   centrifugal compressors, 254–255  
   counter-swirl position, 273  
   IGVs, 233, 287, 288  
   pre-swirl position, 273
- H**
- Harmonic filters, 311  
 Hazard (bowtie diagram), 8  
 Hazard and operability (HAZOP) studies, 8  
 Hazardous chemicals, safety regulations, 7  
 Hazen–Williams equation, 24  
 HAZOP, *see* Hazard and operability (HAZOP) studies  
 Head  
   centrifugal performance, 255  
   defined, 244  
 Head coefficient, centrifugal pumps, 348, 349f, 350t–351t  
 Head curve, liquid pipeline systems, 24–26  
 Head end (HE) cycle, 198, 200  
 Header piping design, 42–44  
 Heat recovery oil heater (HROH), 306, 307  
 Helical lobe rotary compressor, 229–231  
   design, 229, 230f  
   operation, 230–231  
 Helmholtz free energy, 242–243  
 Helmholtz resonators, 463, 490–492, 492f, 500, 502  
 Hermetic compressors, 10, 315–317  
 Hetzel equation, 24  
 High pressure gas cooling, 70  
 High-pressure seal oil, 214  
 High speed oil free intelligent motorcompressor (HOFIM), 315–316  
 History, pump, 100–103  
 Homologous relations, centrifugal pumps, 347  
 Horizontal pumps, 106, 115–117  
 Hub–hub coupling connection, 324  
 Hydraulic accumulator, 344–346  
 Hydraulics  
   gas pipeline, 65, 66f  
   liquid pipeline, 19, 20f  
 Hydraulic simulation, 70–73  
   for assessment, 72–73  
 Hydraulics profile, gas pipeline, 71f  
 Hydrodynamic bearing, 211, 212f
- I**
- Ideal gas laws, 237, 238  
 IEC, *see* International Electrotechnical Commission (IEC)  
 IGCC (integrally geared centrifugal compressor), 231–234  
   bearings, seals and gears, 233–234  
   design, 231–233  
 IGVs (inlet guide vanes), 233, 287, 288  
 Impeller, centrifugal pumps  
   change, 150, 151f  
   curve characteristics, 145–147  
   design, 107–109  
   design theory, 141–143  
   destroyed by cavitation, 154f  
   selection, 138–140  
   specific speed of, 144–145  
   suction specific speed, 165  
   under-filing and over-filing, 150, 152f  
   volute chipping, 150, 153f  
   volute inserts, 150, 153f  
 Impeller(s)  
   centrifugal compressors, 206, 224–227  
   erosion, 261  
 Implosion, 154  
 Incipient surge, defined, 221  
 Induction motors, 307–308, 310  
 Industrial compression system, dynamic instabilities in, 394, 395–402, 396f, 396t, 397t, 398f, 399f, 400f–401f, 401t, 402f  
 Industrial gas turbines, 280, 292, 293f  
 Inertia  
   centrifugal pumps, 352–353, 352f, 353f  
   rotor, on ESD, 393, 394f, 395f  
 Inertia number, 405–408, 407f–408f, 407t  
 Injected seal oil, 214, 215  
 Inlet guide vanes (IGVs), 233, 287, 288  
 Instrumentation, for centrifugal compressor, 262  
 Intake system, air, 286  
 Integral engine/compressors, 322–323  
 Integrally geared centrifugal compressor (IGCC), 231–234  
   bearings, seals and gears, 233–234  
   design, 231–233

- Integrally-gearred compression systems, 402–405, 403f, 403t, 404f–405f
- Integral reciprocating compressor frame, 185
- running gear, 181, 182f
- Integrated compressor line (ICL), 203, 205f
- Intensifier, defined, 218
- Interchange compression, 6
- Intercooler, defined, 198
- Internal combustion engines, 320–323
- advantages and disadvantages of, 333–334
- design, 320–322
- general, 320
- integral engine/compressors, 322–323
- Internal return rate (IRR), 312, 314
- Internals, centrifugal compressors, 205–209
- International Electrotechnical Commission (IEC), 11, 97
- International Organization for Standardization (ISO), 11, 97
- Inverse reduced temperature, defined, 243
- Isentropic compression, 243, 244, 255, 256, 264
- Isentropic efficiency, 244, 250
- ISO, *see* International Organization for Standardization (ISO)
- Isothermal compression, 244
- J**
- J-curves graph, 68
- Joukowski equation, 55
- Joule-Thompson effect, 294
- K**
- Kinetic pumps
- family of, 101f
- types, 99
- L**
- Labyrinth seals, 206, 214, 217
- Lateral compression, 6
- Lateral rotordynamics, 537–540, 538f–540f
- LCC, *see* Long-term life cycle costing (LCC)
- Length, cost of a pipeline and, 1
- Life Cycle Cost analysis, 314
- Limits in performance, centrifugal compressors, 258–260
- Liquid fuel system, 299, 300f
- Liquid pipeline systems, 2–4
- configuration, 28–37
- contamination in, 44–52
- definitions, 3, 4f
- design, 19–28
- considerations for system curves, 27–28
- curve development example, 26–27
- head curve, 24–26
- hydraulics, 19, 20f
- pipe size and selection, 19–24
- piping system, 34–44
- pressure surges in, 55–61
- pumps for, 99–100
- pump station piping design, *see* Piping design, pump station terminal design, 52–61
- unique aspect of, 4
- Liquids
- effects of vapor voids in, 500, 500f
- operational hazards of, 9
- vapor voids in, 500, 501t
- Liquid vs. gas applications, 499–502
- cavitation, 499, 500f
- effects of vapor voids in liquids, 500, 500f
- flashing, 499
- pulsation filters (dampeners) in liquid systems, 500–502
- speed of sound in liquids piping, 499–500, 501f
- Liquified natural gas (LNG), 297
- Loading, rod, 201–202, 271
- London Bridge Waterworks, 103
- Long-term life cycle costing (LCC), 15
- Looping *versus* compression, gas pipelines, 66f, 69–70
- LOPC, *see* Loss of primary containment (LOPC)
- Loss of primary containment (LOPC), 6
- Lower heating value (LHV), 294
- Low-pass filter, 381
- Lube oil cooling, 70
- Lube oil-water cooling, 70
- Lubricated/flooded screw compressor, 229, 230f
- Lubricated gear couplings, 325
- Lubrication regimes, centrifugal pumps, 111, 112f
- Lubrication systems
- centrifugal compressors, 211, 213
- coolers, lube oil, 213
- for gas turbines, 289–292
- aeroderivative, 291–292
- industrial, 292, 293f
- reciprocating compressors, 193, 194–196
- M**
- Mach number, 260
- Magnetic bearings, 211, 212f, 560–561
- MAOP, *see* Maximum allowable operating pressure for the pipeline (MAOP)
- Maps, performance
- centrifugal compressor, 255–257
- reciprocating compressor, 251–254
- Mars, 281
- Matching, component, 302
- Match point, defined, 301
- Materials, for compressor cylinders, 185, 186
- Maximum allowable operating pressure for the pipeline (MAOP), 93
- Maximum allowable shaking forces, API 618 Standard, 509–510
- Maximum Operating Pressure (MOP) limits, 55, 57
- Mean flow
- on acoustic TM for pipe element, 467–468
- Mean time between repairs (MTBR), 314
- Measurement units and conversion factors, 175–177
- Mechanical analysis, 533–588

- API 618 Standard, 502–503, 503f, 504
- centrifugal compressors, 584–588, 586f, 587f
- overview, 533
- of piping systems, 563–588
  - adding damping to mechanically resonant systems, 577–583, 577f, 578f, 579, 580f, 582f
  - centrifugal compressors, 584–588, 586f, 587f
  - excitation mechanisms, 563–564, 564f
  - forced response analysis, 572–576
  - small-bore attachments, 569–572
  - thermal analysis, 583–584
  - unbalanced forces, 566–569, 568f
  - vibration and stress, 564–566, 565f, 566f, 567f
- of rotating equipment, 536–563; *see also* Rotordynamics
  - balancing, 561–563, 562f–563f
  - general, 536–537
  - lateral rotordynamics, 537–540, 538f–540f
  - specific machinery considerations for rotordynamics, 551–561
  - stability, 540–541, 541f
  - torsional rotordynamics, 541–551, 542f–544f, 546f, 548f
  - vibration, basic aspects of, 533–536, 534f, 535f
- Mechanical dry seals, 216, 217
- Mechanical efficiency, 250
- Mechanical hazards, 10–11
- Mechanical natural
  - frequency (MNF), 535–536, 535f–536f
- Mechanical resonance
  - mechanical natural frequency and, 535–536, 535f–536f
- Mechanical seals, centrifugal pumps, 109–114, 115f
  - application chart for, 112–113, 115f
  - basic flush plans for, 113
- equilibrium between forces for, 111, 113f
- lubrication regimes, 111, 112f
- materials used, 111, 114f
- pressure and temperature effect on, 111, 113f
- pressures apply to, 110
- pusher type of, 111, 112f
- tuning, 111
- Metallic element couplings, 325, 326f
- Methane, Wobbe index for, 294
- Metric system, 175
- Minimum flow limits, centrifugal pumps, 163
- Mitigation barriers (bowtie diagram), 8
- Mixed lubrication, 111
- Mixture composition, on centrifugal compressor performance, 262–264
- Molecular weight (MW) of natural gas mixture, 238–240
- Monitoring system
  - centrifugal compressors, 220–223
  - degradation, centrifugal compressor performance, 264–266, 267f
  - reciprocating compressors, 197
- Moody's diagram, 25f
- MOP, *see* Maximum Operating Pressure (MOP) limits
- Motor pipeline compressor (MOPICO), 315–317
- Motors
  - rotordynamics and, 554–558, 556f, 557f
  - VFD-controlled, 555–558
- Multiple source pulsation, 521–523, 522f
- Multi-shaft compressor, 231–234
  - bearings, seals and gears, 233–234
  - design, 231–233
- Multi-stage centrifugal compressors, 551
- Multi-stage pump, 106
- N**
- National Energy Board Regulations SOR/99-294, 7
- Natural gas, 293–294
  - fuel system, 297–299
  - LNG, 297
- Net positive inlet pressure (NPIP) for reciprocating pump, 172
- Net Positive Inlet Pressure Available (NPIPA) for reciprocating pump, 173
- Net Positive Inlet Pressure Required (NPIPR) for reciprocating pump, 173 for rotary pump, 170
- Net Positive Suction Head (NPSH), 157–158
  - breakdown curves, 160f
- Net Positive Suction Head Available (NPSHA), 158, 159f
- Net Positive Suction Head Required (NPSHR), 158–159, 160f
- Net present values (NPVs), 74, 210, 312, 314, 318f, 319f
  - analysis (case study), 77–78
- Network, gas pipeline, 70, 71f
- Neural network based PEM models, 615–620, 616f, 617f, 618f, 619f, 620f
- Newtonian fluids, 21
- Newton-Raphson method, 379
- Nitrogen, surge relief valves, 59, 60f
- Nitrogen oxides, formation, 294–295
- Noise, compressor and pump stations
  - noise criteria limits, 595–600, 597t, 598f, 599f, 600t
  - noise level
    - parameters, 594–595
    - predictions, compressor stations, 601–607
    - survey, 608–612
    - noise mapping methodology, 608–610, 609f, 610f
- Noise criteria (NC)
  - index, 595, 598
  - limits, 595–600, 597t, 598f, 599f, 600f, 600t
- Noise emissions, 331, 332, 334
- Noise level parameters, 594–595
- Noise measurement, 594–607
  - noise criteria limits, 595–600, 597t, 598f, 599f, 600t

- noise level parameters, 594–595
- predictions of noise levels from compressor stations, 601–607
- Noise suppression during blow-down, 496–499, 497f–499f
- Noise surveys
  - example application on a compressor station, 610–612
  - noise mapping methodology, 608–610, 609f, 610f
- Nomenclature for compression performance, 237, 238t
- Non-functional requirements, dependability, 12, 13f
- Non-isothermal blowdown, 453–457
- Non-lubricated/dry screw compressor, 229
- Non-Newtonian fluids, 21
- Non-overloading characteristic curve, 147
- NOVA Gas Transmission system, 209
- NOx emissions from gas turbines, 612–623
  - AP-42 emission factors, 613
  - CEM measurements, 613–615, 614f, 615f
  - neural network based PEM models, 615–620, 616f, 617f, 618f, 619f, 620f
  - PEM implementation, 620–623, 621f–623f
- Nozzle loading, centrifugal pump, 114–118
  - horizontal pumps, 115–117
  - vertical inline pumps, 116t, 117–118
- NPIP, *see* Net positive inlet pressure (NPIP)
- NPIPA, *see* Net Positive Inlet Pressure Available (NPIPA)
- NPIPR, *see* Net Positive Inlet Pressure Required (NPIPR)
- NPSH, *see* Net Positive Suction Head (NPSH)
- NPSHA, *see* Net Positive Suction Head Available (NPSHA)
- NPSHR, *see* Net Positive Suction Head Required (NPSHR)
- NPV, *see* Net present value (NPV)
- Number of units
  - compressor station configuration, 76–77
  - liquid pipeline systems, 30–33
- O**
- Occupational Safety and Health Administration (OSHA), 97
- Onsite testing, 228
- Open, acoustic boundary conditions, 488–490
- Operating cost
  - of compressor, 73–74
  - pipelines, 1
- Operating limits, API 618 Standard, 507
- Operational hazards, 9–11
- Operations, compressors
  - centrifugal, 223–228
    - diffuser, 228
    - fluid properties, effect of, 228
    - impellers, 224–227
    - performance characteristics, 223–224
  - considerations, 274–276
    - parallel operation, 276
    - series operation, 275–276
    - shutdown, 276
    - startup, 274–275
  - limitations, 271–272
  - reciprocating, 198–200
  - screw, 230–231
- Optimization, reciprocating compressors, 200–201
- Optimization process, gas pipeline systems, 65–69
  - alternatives, 68–69
  - considerations, 65–66, 69
- Organic Rankine bottoming cycle, 306
- Orifice plate
  - acoustic transfer matrix for throttle element, 475, 475f
- OSHA, *see* Occupational Safety and Health Administration (OSHA)
- OSHA 1910.119 Process safety management, 7
- Over-compression discharge pressure, 231
- Overhung centrifugal compressor, 203, 204f
- Overload, defined, 260
- Overloading characteristic curve, 147
- P**
- Packings, reciprocating compressors, 193, 194f
- Parallel configuration
  - of compressor for gas compression, 76
  - pumping piping, 36, 37f
  - of pumps in liquid pipeline system, 29–30
  - standby unit, 79, 80f
- Parallel operation, compressors, 276
- Particle sizes
  - pump selection and, 23
- PCV, *see* Pressure control valve (PCV)
- PEM implementation, 620–623, 621f–623f
- Peng-Robinson EOS, 241
- Pentane vapor, 307
- Percentage of time, 32
- Perfect gas law, 237, 238
- Perforated tube mufflers, 492, 494f
- Performance, pumps, *see* Pumps, performance of
- Performance correction chart, for viscous liquids, 161, 162f
- Performance modifications, 150, 151f–153f
- Performance(s), compressors, 237–276
  - basic aspects, 237–247
    - behavior, 243–244
    - efficiency, 244–245
    - flow, 245
    - gas properties, 237, 238–243
    - general, 237
    - head, 244
    - nomenclature, 237, 238t
    - power, 245–247
  - centrifugal compressors, 254–267
    - characteristics, 223–224
    - curves, 254–257
    - degradation monitoring, 264–266, 267f

- dynamic performance characteristics, 254–260
- general, 254
- limits, 258–260
- mixture composition on, 262–264
- selection and sizing, 260–261
- testing, 261–262
- gas turbines, 299, 300–305
  - calculations, 302, 303f, 304–305
  - characteristics, 299, 300, 301, 302f, 303f
  - field testing, 305
- overview, 237
- reciprocating compressors, 247–254
  - discharge temperature, 251
  - flow, 247–249
  - general, 247
  - maps, 251–254
  - piston speed, 254
  - power, 249–251
- system characteristics, 267–276
  - adjustments, 272–274
  - comparison, 270, 271f
  - curves, 267–270
  - general, 267
  - operating considerations, 274–276
  - operating limitations, 271–272
- Personnel, operational hazards of, 9
- Physical operation
  - centrifugal compressors, 223–228
    - diffuser, 228
    - fluid properties, effect of, 228
    - impellers, 224–227
    - performance characteristics, 223–224
  - reciprocating compressors, 198–200
- PID controller, 380
- Pilot-operated PRVs, 526
- Pilot-operated relief valves, 429–434, 430f, 431f
- Pipe element
  - acoustic transfer matrix for, 464–471, 466f, 471f
- Pipeline-pump operational control, 148–150
- Pipeline systems
  - advantages, 1
  - gas, 4–6, 5f; *see also* Gas pipeline systems
  - limitations, 1
  - liquid, 2–4, 3f, 4f; *see also* Liquid pipeline systems
  - overview, 1, 2f
  - process safety, 6–11
  - relative transportation cost for petroleum products, 2f
  - safety, 6–17
  - trends in primary energy consumption, 2f
- Pipe model, station and gas pipeline blowdown, 449–450
  - analytical, 449–450
- Pipe size
  - cost and, 21–22
  - liquid pipelines, 19–24
  - pipng design and, 39, 41
- Piping design, pump station, 34–44
  - configuration, 34–38
  - fast start-up valve positions, 37–38
  - general station design, 34–38
  - header piping design, 42–44
  - hydraulic considerations, 41–42
  - improvements in, 38–39
  - layout, 39, 40f
  - objectives, 38–39
  - parallel arrangement, 36, 37f
  - physical requirements for, 34
  - pipe sizing, 39, 41
  - series arrangement, 36, 40f
  - series/parallel configuration, 36, 37f
  - valve selection, 44
- Piping system
  - analysis, 504
  - station design for reciprocating pumps, 127, 128f
    - discharge piping, 129
    - suction piping, 127–128
    - suction vessel, 129
- Piping velocity limitations, 34
- Piston, 100
  - pumps, 122–123
  - speed, reciprocating compressors, 254
  - type check valves, dynamics of, 422–424, 422f
- Piston displacement (PD), 247
- Plate valves, 187, 189f, 190f
- Platinum™, 197
- Plunger pumps, 121–122, 123f
- Pneumatic clearance valve, 187, 188f
- Poly-etheretherketone (PEEK), 190
- Polytropic compression, 243–244, 255, 256
- Poppet valves, 187, 189f, 190, 191f
- Positive displacement pumps, 119–129; *see also* Pump(s)
  - overview, 99, 100f
  - performance of
    - net positive pressures, 172–173
    - power and efficiency, 169–170
  - reciprocating pump acceleration head, 171–172
  - reciprocating pump flow characteristics, 171, 172f
  - reciprocating pump selection, 173–175
  - rotary pump performance chart, 167, 168f, 169f
  - rotary pump slips and clearance, 170
  - system head curves and rotary pump curve, 170–171
- pulsation dampeners, 124–126
- reciprocating pumps, 121–124; *see also* Reciprocating pumps
  - rotary pumps, 102f, 119–121, 122f; *see also* Rotary pumps
- Power
  - compressors, 245–247
  - plunger pumps, 124
  - range, 331, 332, 333
  - reciprocating compressors, 249–251
- “Power” backup, compressor station, 79
- Power Test Code (PTC) 10 test, 228, 261
- Power turbines, 554
  - rotordynamics and, 554



- Power usage distribution (case study), 81–83
- Predictive Emission Monitoring (PEM) system
  - implementation, 620–623
- Preheat correction, 251
- Pre-rotation position, for control purposes, 273
- Pressure control valve (PCV), 34, 43–44, 213
  - sudden closure of, 57–58
- Pressure head
  - liquid pipeline systems, 24
- Pressure limitations, pipeline
  - design and, 21, 34
  - MOP and, 55
- Pressure relief, pipeline design and, 34, 58–61
- Pressure relief valves (PRV), 213
  - American petroleum Institute (API 520) standards, 526–527
  - chattering, 526
  - cycling, 525
  - example of PRV stability calculations, 529t
  - fluttering, 525–526
  - instability criteria of, 525–530
  - pilot-operated, 526
  - remote sensing pop-action pilot, 526
  - spring loaded, 526
- Pressure surges in pipelines
  - automated surge relief installation, 60–61
  - causes of, 55
  - nitrogen loaded surge relief valves, 59, 60f
  - pump shutdown and, 56
  - pump startup and, 55–56
  - relief measures, 58–61
  - valve closure and, 56
- Pressure–volume characteristics, of compressors, 270, 271f
- Pressurized oil bearings, 560–561
- Pre-swirl position, guide vanes, 273
- Prevention barriers (bowtie diagram), 8
- Princess Compressor Station (Alberta, Canada), operational hazards, 10
- Probability theory, 30–32
- Process safety, 6–11
  - guidance in API RP1173, 7
  - hazardous chemicals, 7
  - operational hazards, 9–11
  - Process Safety Management (PSM), 6–7
  - risk assessment, 7–9
- Process Safety Management (PSM), 6–7
  - risk assessment, 7–9
- Pseudo-plastic fluids, 21, 22f
- PSM, *see* Process Safety Management (PSM)
- Pullout torque, defined, 309
- Pulsation analysis, API 618 Standard, 502–504, 503f
- “Pulsation and Vibration Control in Positive Displacement Machinery Systems for Petroleum, Petrochemical, and Natural Gas Industry Services,” 516
- Pulsation attenuation devices, 203
- Pulsation dampeners, 124–126
  - dynamic, 125
  - suction, 125–126
- Pulsation filters (dampeners) in liquid systems, 500–502
- Pulsation generated by a reciprocating compressor, 523–525, 523f–525f
- Pulsation generation, 480–487, 481f–482f, 483f–484f, 486f–487f
  - flow-generated pulsation from throttling elements, 480–482, 481f–482f
  - flow-generated single-tone pulsation from closed end side branch, 482–485, 483f–484f
  - by reciprocating compressors and pumps, 485–487, 486f–487f
- Pulsation guidelines, API 618 Standard, 505
- Pulsation suppression, techniques for, 490–499
  - noise suppression during blow-down, 496–499, 497f–499f
  - reactive silencers, 490–493, 491f–493f
  - spoilers for, 493–496, 494f–496f
- Pulsation transmission, through piping elements, 463–480
  - acoustic transfer matrix
    - for centrifugal compressor, 479–480, 479f
    - for pipe element, 464–471, 466f, 471f
    - for throttle element, 472–478, 473f, 474t, 475f, 476f, 477f
    - for a volume element, 478–479, 478f
  - overview, 463–464
- Pulse width modulation, 311
- Pump configurations
  - centrifugal pumps, 107
  - liquid pipeline systems
    - general, 28–29
    - number of units, 30–33
    - pumps in parallel, 29–30
    - pumps in series, 29
    - pump station configuration, 34–37
- Pump four quadrant charts, 354–357, 355f, 357f
- Pump head capacity (H-Q) curve, 145–147
- Pumping
  - dependability for, 14–15
- Pump(s)
  - centrifugal, 9, 100, 104–118; *see also* Centrifugal pumps
  - energy conversion and, 99
  - family, 99–100
  - history, 100–103
    - chronologically listed events, 103
  - kinetic, 99, 101f
  - for liquid pipeline stations, 99–100
  - performance curves, 137–138, 139f
  - positive displacement, 119–129; *see also* Positive displacement pumps
  - selection for liquid pipeline system, 19–24
- Pumps, performance of, 131–178
  - API gravity and SG, relationship, 133–136
  - centrifugal pumps
    - affinity laws, 148, 149f
    - cavitation in, 154–160

- centrifugal impeller design theory, 141–143
  - coverage chart, 138
  - impeller curve characteristics, 145–147
  - impeller selection, 138–140
  - limits, 163–166
  - performance modifications, 150, 151f–153f
  - pipeline-pump operational control, 148–150
  - pump performance curves, 137–138, 139f
  - pump power and efficiency, 150
  - specific speed, 143–145, 146f
  - system curve, 140, 141f
  - viscous liquids and, 160–163
  - measurement units and conversion factors, 175–177
  - overview, 131
  - of positive displacement pumps, 167–175
  - surge in system operation, 166–167
  - system design standards and, 177–178
  - system head, 131–133
  - vs. pipeline system curve
  - Pump shutdown, pressure surge and, 56
  - Pump startup, pressure surge and, 55–56
  - Pump station configuration
    - general, 28–29
- R**
- Radial flow pumps, 105, 106f
  - Radial split (end cover), 206
  - RAM models, *see* Reliability, Availability and Maintainability (RAM) models
  - Rankine bottoming cycle, organic, 306
  - Ratio of specific heats, 240–241
  - Reactive silencers for pulsation suppression, 490–493, 491f–493f
  - Reciprocating compressors, 179–203
    - advantages and disadvantages of, 335
    - bearings and lubrication systems, 193, 194–196
    - capacity (flow) control, 187, 188f, 189f
    - control system, 196
    - design
      - considerations, 203
      - general, 179–181
    - driven by VFD-controlled motors, 555–558
    - frame and cylinders, 183–187
      - cylinders, 185–187
      - foundations, 183–184
      - integral compressor frame, 185
      - separable compressor, 184–185
    - gas cooling, 198
    - installation, tuning out difficult torsional vibration problem in (case study), 327, 328, 329f
    - integral, 181, 182f, 185
    - monitoring system, 197
    - optimization, 200–201
    - overview, 179
    - packings, 193, 194f
    - performance, 247–254
      - discharge temperature, 251
      - flow (capacity), 245, 247–249
      - general, 247
      - maps, 251–254
      - piston speed, 254
      - power, 249–251
    - physical operation, 198–200
    - pressure–volume characteristic, 270, 271f
    - pulsation generated by, 485–487, 486f–487f, 523–525, 523f–525f
    - rod loading, 201–202
    - rotordynamics and, 552–553, 552f, 553f
    - running gear, 181, 182–183
    - separable, 181, 182f, 183, 184–185
    - start-up and shutdown, 197
    - types, 179–181
    - valves, 187, 189–192, 193f
  - Reciprocating pumps, 121–124
    - acceleration head, 171–172
    - disadvantages, 123
    - discharge piping, 129
    - family of, 101f
    - flow characteristics, 171, 172f
    - piston pumps, 122–123
    - plunger pumps, 121–122
    - power plunger pumps, 124
    - pulsation generated by, 485–487, 486f–487f
    - selection
      - charts, 173–174
      - pump power calculations, 174–175
      - theoretical pump volume calculation, 174
      - speed rating, 126–127, 127t
      - station piping design for, 127, 128f
      - suction piping, 127–128
      - suction vessel, 129
      - torque characteristics, 126, 127f
      - type, 99
  - Re-circulation in centrifugal pumps, 164–166
  - Recycle system around compressors arranged in series, 409–410, 409f, 410f–411f
  - Recycling, compressor stations, 93
  - Redlich-Kwong EOS, 241
  - RefProp, mixture property program, 243, 264
  - Regular internally-pressurized fluid film bearings, 560
  - Reliability; *see also* Dependability, pipeline system
    - concept, 11
    - standardization, 11
  - Reliability, Availability and Maintainability (RAM) models, 15–16, 17f
  - Relief valve dynamics, 427, 429–444
    - example, 436–441, 438f–441f
    - field tests, 441–444, 442f, 443f–444f
    - pilot-operated relief valves, 429–434, 430f, 431f
    - solution technique, 434–436
  - Remote sensing pop-action pilot PRVs, 526
  - Resistance coefficient, 25–26

- Resonance  
 for fixed-speed machine, 535f  
 for variable speed machine, 536f
- Restaging, 150, 152f
- Rexnord, 325
- Reynolds numbers (Re), 24, 26, 45  
 defined, 260  
 noise suppression during blow-down, 484, 496–497
- Rising characteristic curve, 146, 147f
- Risk assessment, pipeline system, 7–9
- Rod loading, reciprocating compressors, 201–202, 271
- Rod reversal, defined, 201
- Rolls Royce, 281, 287, 289f, 290
- Rotary compressors, types, 229
- Rotary pumps, 102f, 119–121, 122f  
 capability range, 120t  
 curve, system head curves and, 170–171  
 damage caused by hard contaminant, 121f  
 family of, 102f  
 flow/capacity control, 121  
 inadequate suction conditions correction, 173  
 performance chart, 167, 168f, 169f  
 power and efficiency, 169–170  
 pulsation and pressure relief, 120–121  
 slips and clearance, 170  
 system configuration, 122f  
 types, 99, 119
- Rotating equipments, 536–563  
 balancing, 561–563, 562f–563f  
 general, 536–537  
 lateral rotordynamics, 537–540, 538f–540f  
 specific machinery considerations for rotordynamics, 551–561  
 stability, 540–541, 541f  
 torsional rotordynamics, 541–551, 542f–544f, 546f, 548f
- Rotating stall, *see* Surge
- Rotordynamics  
 balancing and, 561–563, 562f–563f  
 bearings and, 560–561  
 centrifugal compressors and, 551–552  
 centrifugal pumps, 553–554  
 gas/power turbines, 554  
 gearboxes and couplings, 558–560, 559f, 560f  
 lateral, 537–540, 538f–540f  
 motors, 554–558, 556f, 557f  
 reciprocating compressors, 552–553, 552f, 553f  
 stability, 540–541, 541f, 561–563  
 torsional, 541–551, 542f–544f, 546f, 548f
- Rotors, 285  
 inertia, on ESD, 393, 394f, 395f
- Running gear, 181, 182–183
- S**
- Safety, pipeline systems, 6–17  
 dependability and, 11–17  
 process safety, 6–11
- Safety systems, compressor station, 96
- SCADA, *see* Supervisory control and data acquisition (SCADA) system
- Scavenge pumps, 292
- Screch tones, 603–604
- Screw compressors, 229–231  
 design, 229, 230f  
 operation, 230–231
- Scrubbers, compressor station, 90–91
- Sealing system, centrifugal compressors, 205–209, 213–220  
 dry gas seals, 216–219  
 emerging gas seal technology, 220  
 general, 213–214  
 wet oil seals, 214–215
- Seal-less centrifugal pump type, 99
- Seal(s)  
 IGCC, 233–234  
 oil, 215
- Selection, performance of centrifugal compressors, 260–261
- Self-excited vibration, 551
- Separable reciprocating compressor  
 frame, 184–185  
 running gear, 181, 182f, 183
- Series configuration  
 of compressor for gas compression, 76  
 pumping piping, 36, 40f  
 of pumps in liquid pipeline system, 29  
 standby unit, 79, 80f
- Series operation, compressors, 275–276
- Series-parallel configuration  
 of compressor for gas compression, 76  
 pump station piping, 36, 37f
- Service Factor, 324
- SG, *see* Specific gravity (SG)
- Shaft(s)  
 arrangements, for gas turbines, 284–285  
 centrifugal compressors, 206
- Shaking forces, standards and guidelines, 509–510
- Shared VFDs, 314
- Shear rate, 21, 22f
- Shutdown, 197, 276
- Shutdown control  
 ESD, 94, 95f  
 SSDL, 94, 95f  
 SSDR, 93, 94f
- Shutoff, rise to  
 pipeline design and, 23
- Side-branch mufflers, 491
- Siemens, 281
- Simple compression systems, 372–374, 372f–373f, 374f
- Single-source pulsation, 520–521, 520f–521f
- Single-stage pump, 106
- Single-suction pump, 106
- SI units, 175
- Sizing, performance of centrifugal compressors, 260–261
- Slab gate valves, 44
- Small-bore attachments  
 mechanical analysis of piping systems and, 569–572
- Small bore connections (SBCs), 569–572  
 defined, 569  
 definition chart for different pipe sizing, 569f  
 design best practices, 571–572  
 failures of, 569, 571

- general, 569–571
- guidelines for screening, 572
- isolating, 572
- orientation of, 571
- small bore and mainline connection and piping definitions, 570f
- small-bore attachments on a reciprocating compressor, 570f
- Snubbers, 500–502, 501f
- Soave-Redlich-Kwong EOS, 241
- Soft couplings
  - elastomeric, 327
  - steel-spring, 327
- Solar bearing, 209, 210f
- Solar Centaur, 287, 297
- Solar low NO<sub>x</sub> (SoLoNO<sub>x</sub>), 296
- Solar Saturn, 281, 282f
- Solar Turbines, 281, 283
- Solids concentrations
  - pump selection and, 23
- Solution techniques, 487–488
  - dynamic instabilities, 382–386, 382f–383f, 384f, 385f, 386f
  - pumping systems, 341–342, 342f
  - relief valve dynamics, 434–436
- Sound
  - intensity, 594–595
  - speed in liquids piping, 499–500, 501f
- Sound pressure level (SPL), 594–597, 608, 611f
- Sour oil, 215
- Spark-ignited engines, 320
- Specific gravity (SG)
  - API gravity and, relationship, 133–136
  - pipeline design and, 22–23
  - pump selection and, 23
  - of some hydrocarbon liquids, 136t
- Specific heat
  - pipeline design and, 21
  - ratio of, 240–241
- Specific speed, efficiency and, 143–145, 146f
- Speech Interference Level (SIL), 598
- Speed drives, variable, 310, 311–315
  - fluid coupling, 314, 315f
  - VFD, 310, 311–314
- Speed of sound in liquids piping, 499–500, 501f
- Speed rating, reciprocating pumps, 126–127
- Spoilers, for pulsation suppression at source, 493–496, 494f–496f
- Spring loaded PRVs, 526
- SSDL, *see* Station shutdown lockout (SSDL)
- SSDR, *see* Station shutdown restartable (SSDR) mode
- Stability
  - defined, 260
  - rotordynamics, 540–541, 541f, 561–563
- Stable characteristic curve, 147
- Stall, 221–222
- Standards
  - API, *see* American Petroleum Institute (API)
  - compressor, 96–97
  - couplings, 329–330
  - design, *see* Design standards
  - pump and system design, 177–178
- Standards and guidelines, 502–518
  - API 618 Standard, 502–510, 503f
  - API 674 Standard, 510–512
  - shaking forces arising from
    - pressure pulsation, 512–513, 512f–513f
- Standby units, 78–80, 81f
- Startup, 197, 274–275
- Static head
  - liquid pipeline systems, 24
  - velocity and, 25
- Station bypass valve, 34, 35f, 36
- Station check valve, 35f, 36
- Station discharge valves, 34, 35f, 36, 44
- Station isolation valves, 35f, 36
- Station level control, compressor stations, 92
- Station shutdown lockout (SSDL), 94, 95f
- Station shutdown restartable (SSDR) mode, 93, 94f
- Station suction valve, 34, 35f, 36
- Stators, defined, 285
- Steam condensation-induced water hammer, 359–361, 360f
- Steam injection, 296
- Steel-spring soft couplings, 327
- Steep characteristic curve, 146, 147f
- Stonewall, 259, 272
- Stress
  - mechanical analysis of piping systems, 564–566, 565f, 566f, 567f
- Styrene transfer system, 361–365, 361f–362f, 363f, 364f–365f, 366f
- Subsynchronous vibration, 551
- Suction lift, piping design, 34
- Suction piping
  - for reciprocating pumps, 127–128
  - size and design, 34
- Suction pulsation dampeners, 125–126
- Suction specific speed, 165–166
- Suction throttling, 93
- Suction valve, 187, 189f, 190, 191, 192f
- Suction vessel, for reciprocating pumps, 129
- Sump system, 34
- Supercharging, defined, 320
- Supercompressibility, defined, 238
- Supersonic ejectors; *see also* Two-stage supersonic ejectors
  - in operation, 631–634, 632t, 633f, 633t, 634t
  - primary challenges of, 625–626
  - 1st stage, 625–632, 625f, 626f, 627f, 630f, 631f, 632
  - 1st stage supersonic ejector, 625–632, 625f, 626f, 627f, 630f, 631f, 632
  - two stages of ejector, 626–628, 626f–628f
- Supervisory control, compressor stations, 92
- Supervisory control and data acquisition (SCADA) system, 93
- Surge
  - air compressor, 286–287
  - on compressor, 221–222
  - control system, 222–223
  - dynamic compressors, 272

- operating range by, 260
- protection for centrifugal compressors, 270
- relief valves, 59, 60f
- vessel, 59
- Survey
  - noise, compressor and pump stations, 608–610, 609f, 610f, 612–623
- Swing type check valves; *see also* Check valve dynamics
  - description, 411–412, 412f
  - dynamic behavior of, 413–417, 414f, 416f–417f
  - slamming characteristics, 417–421
- Synchronous motors, 308–310
- System characteristics, compressors, 267–276
  - adjustments, 272–274
  - comparison, 270, 271f
  - curves, 267–270
  - general, 267
  - operating considerations, 274–276
  - parallel operation, 276
  - series operation, 275–276
  - shutdown, 276
  - startup, 274–275
  - operating limitations, 271–272
- System curve, centrifugal pumps, 140, 141f
- System head, 131–133
  - vs.* specific gravity, pumps delivering the same pressure, 133f
- System head curves
  - of centrifugal pumps, 140, 141f
  - liquid pipeline systems, 24–26
  - pump *versus* pipeline, 132f
- T**
- “Tail effect,” 45
- Tangency rule, 598
- Taurus, 281
- TB Woods flexible disk couplings, 325
- TCO, *see* Total cost of ownership (TCO)
- Technical Committee 56 (TC56), 11
- Temperature effect, pipeline design, 21
- Temperature profiles, gas pipeline, 72f
- Temperature rise in centrifugal pumps, 163–164
- Terminal, liquid pipeline systems, 4
- Terminal piping design, 52–61
  - components of, 54
  - layout of, 54
  - pressure surges, 55–56
  - transient analysis, 56–58
- Testing, performance, centrifugal compressors, 261–262
- Test tolerances
  - pipeline design and, 23
- Thermal analysis
  - mechanical analysis of piping systems and, 583–584
- Thermal efficiency, 331, 332, 334
- Threats (bowtie diagram), 8
- Throttle element
  - acoustic transfer matrix for, 472–478, 473f, 474t, 475f, 476f, 477f
  - flow-generated pulsation from, 480–482
- Throttling, suction and discharge, 272
- Throttling elements
  - flow-generated pulsation from, 480–482, 481f–482f
- Thrust force, in two-stage centrifugal compressor, 206, 208f
- Tilting pad bearings, 209, 210, 211f, 212f
- Titan, 281
- Top Event (bowtie diagram), 8
- Torque characteristics, reciprocating pumps, 126, 127f
- Torque coefficient, centrifugal pumps, 348, 349f, 350t–351t
- Torsional analysis, 324, 541–543, 546–548, 547f–548f
- Torsional modeling, 543–546, 545f, 546f
- Torsional natural frequencies (TNF)
- Torsional rotordynamics, 541–551, 542f–544f, 546f, 548f
  - importance of, 541–543
  - torsional analysis, 546–548, 547f–548f
  - torsional modeling, 543–546, 545f, 546f
  - torsional solutions, 548–551, 549f, 550f
- Torsional solutions, 548–551, 549f, 550f
- Torsional vibration (TV), 555–556
  - problem in reciprocating compressor installation, case study, 327, 328, 329f
- Total cost of ownership (TCO), 15
- Totally enclosed fan-cooled motor cooling, 310, 311f
- Totally enclosed forced ventilation, 310
- Totally enclosed water-to-air cooled motor cooling, 310, 311f
- TransCanada Pipelines, 281
- Transfer matrix (TM)
  - mean flow on acoustic TM for pipe element, 467–468
- Transient analysis
  - drawbacks, 57
  - objectives of, 56–57
- Transmission, 6
- Turbine inlet temperatures (TITs), 280, 301
- Turbines
  - gas, 554
  - power, 554
- Turbocharging, defined, 320
- Twin-spool gas generator, 285
- Two-stage supersonic ejectors, 626–628, 626f–628f
  - performance of integrated, 629–632, 629f–631f, 631t
- Typical acceleration, 534
- U**
- Unbalanced forces
  - mechanical analysis of piping systems, 566–569, 568f



- Unburned hydrocarbons (UHC), 295
  - Uncontrolled devices, 613
  - Uncontrolled engines, 613
  - Under-compression discharge pressure, 231
  - Unit auxiliary systems, compressor station, 92
  - Unit control systems, compressor station, 92–95
  - “Universal velocity profile,” 46
  - Unloaders, types of, 187, 188f
  - Unstable characteristic curve, 147
  - U.S. Federal Interagency Committee on Urban Noise (FICUN), 599
  - Usage scenario for pipeline stations (case study), 81–85
- V**
- Value
    - of dependability, 12–14
  - ValveAlert™, 197
  - Valve(s)
    - bleed, 287
    - closure, pressure surge and, 56
    - discharge, 187, 189f, 190, 191, 192f
    - plate, 187, 189f, 190f
    - pneumatic clearance, 187, 188f
    - poppet, 187, 189f, 190, 191f
    - pressure control, 213
    - pressure relief, 213
    - reciprocating compressors, 187, 189–192, 193f
    - selection, piping design, 44
    - suction, 187, 189f, 190, 191, 192f
  - Van der Waals mixing rule, 241
  - Vaneless diffusers, 261
  - Vanes
    - guide, *see* Guide vanes
    - IGVs, 233, 287, 288
    - VSVs, 287–288
  - Vapor pressures
    - cavitation and, 155, 156f
    - pump selection and, 23
  - Vapor voids in liquids, 500, 501t
  - Variable compressor geometry, 287–288
  - Variable frequency drive (VFD), 310, 311–314, 315
  - Variable speed drives, 310, 311–315
    - fluid coupling, 314, 315f
    - VFD, 310, 311–314
  - Variable stator vanes (VSVs), 287–288
  - Variable volume clearance pocket (VVCP), 186–187, 199–200
  - Velocity limitations, piping design, 34
  - Vent gas
    - recovering loss from dry gas seals, 624–634
  - Vertical booster pump, 104f
  - Vertical inline pumps, 116t, 117–118
  - Vertical pump (dry pit-type), 106
  - Vertical pump types, 99
  - Vertically suspended pump, 518
  - VFD (variable frequency drive), 310, 311–314, 315
  - VFD-controlled motors
    - reciprocating compressors driven by, 555–558
  - Vibration, 533–536
    - amplitude, 533
    - basic aspects of, 533–536, 534f, 535f
    - defined, 533
    - forced, 551
    - mechanical analysis of
      - piping systems, 564–566, 565f, 566f, 567f
    - MNF and resonance, 535–536, 535f–536f
    - overview, 533–535, 534f, 535f
    - self-excited, 551
    - subsynchronous, 551
    - torsional, 555–556
  - Vibration amplitude, 533
  - Vibration velocity, 534
- Viscosity**
- pipeline design and, 21–22, 23f
  - pump selection and, 23–24
- Viscous liquids**
- centrifugal pumps and, 160–163
  - performance correction chart, 161, 162f
- Volume model, station and gas pipeline blowdown, 446–449**
- analytical solution, 446–448
  - numerical solution, 448–449
- Volumetric efficiency (VE), 199, 200, 248–249**
- Volute chipping, impeller, 150, 153f**
- Volute inserts, impeller, 150, 153f**
- Volute pump, 106**
- VSVs (variable stator vanes), 287–288**
- VVCP (variable volume clearance pocket), 186–187, 199–200**
- W**
- Wafer type check valves, dynamics of, 424–425, 424f
  - Waste heat recovery, gas turbines, 306–307
  - Water cooling, 70
  - Water hammer, 357–358
    - steam condensation-induced, 359–361, 360f
  - Weather-protected type enclosure, 310
  - Weather protection, compressor station, 95
  - Wet oil seals, 214–215
  - What if/checklists, 8
  - Wheel curve, defined, 255
  - Wobbe index, 294, 297
- Z**
- Zero emissions seal (ZES), 220